CLOSING THE GAP BETWEEN GRASSLANDS AND GRAIN AGRICULTURE

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I. INTRODUCTION

Grasslands are among the biomes that have been most extensively degraded or eliminated by the expansion of agriculture.[1] Grasslands are also threatened by development, poor management, and climate change.[2] This expansion of agriculture has prompted intense concern amongst conservation biologists, as grasslands provide critical habitat for thousands of wild plant and animal species. Less attention has been focused on the non-biodiversity ecosystem services that intact natural grasslands provide[3]. Services such as soil protection, carbon sequestration, water purification are essentially taken for granted when ecosystems provide them for free.[4] In contrast, row crop agriculture has received growing recognition as a problematic source of ecosystem *disservices*.[5] As will be discussed in this article, soil erosion, nutrient leakage, weed establishment, loss of soil organic matter, agrochemical and fossil fuel dependence are all

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1. JIM M. SUTTIE ET AL., GRASSLANDS OF THE WORLD 463 (2005).

2. JOHN W. HEAD, GLOBAL LEGAL REGIMES TO PROTECT THE WORLD'S GRASSLANDS 39–57 (2012).

3. *See generally* GRETCHEN C. DAILY, NATURE'S SERVICES: SOCIETAL DEPENDENCE ON NATURAL ECOSYSTEMS (1997). The concept of ecosystem or nature's services was formalized in this volume. Daily brought together many ideas from sources like Aldo Leopold to practitioners of ecological economics during her Ph.D. work at Stanford under Paul Ehrlich. The idea of ecosystem services has been widely adopted in an attempt to value the role that ecosystem processes play in supporting human well-being. In many cases, the objective of using an ecosystem service framework is to place a monetary value on the services provided by nature in order to internalize costs that otherwise fall out of the economic system as externalities.

4. NATIONAL RESEARCH COUNCIL, VALUING ECOSYSTEM SERVICES 17 (2005).

5. Alison G. Power, *Ecosystem services and agriculture: tradeoffs and synergies*, 365 PHIL. TRANS. ROYAL SOC'Y B, 2959, 2964–67 (2010).

disservices that occur as a consequence of converting grasslands to annual, monoculture croplands. There now exists the opportunity to develop agroecosystems that function more like natural grasslands and thus are expected to recapture many of the ecosystem services that grasslands originally provided.[6] The two areas of research deemed most critical to make this transition to a grassland-like agriculture are the breeding of perennial grain crops, and the management of higher diversity cropping arrangements.

In this article, I am going to describe what ecologists perceive as the most important ecosystem services that were sustained by diverse, native grasslands. I will then explain how these services turned into disservices with the conversion of grass to croplands, and finally how a new agriculture, informed by the structure and function of the original native grasslands has the potential to resolve the tradeoff between the provision of food and other critical ecosystem services (Figure 1).[7]

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6. *See generally* Timothy E. Crews et al., *Going Where no Grains Have Gone Before: From Early to Mid-Succession*, 223 AGRIC. ECOSYST. ENV'T 223, 223–38 (2016).

7. The focus of this paper will be how agriculture can capture these ecosystem services by mimicking aspects of naturally occurring grasslands. However, I want to suggest caution about using the term "ecosystem services" as a reason to value some aspect of nature. Aldo Leopold in his highly influential essays published as *The Sand County Almanac* (1968), argued that all members of the land community should have standing simply as fellow members of Earth's biotic community.

> The land ethic enlarges the boundaries of the community to include soils, waters, plants and animals, or collectively: the land. ....In short, a land ethic changes the role of Homo sapiens from conqueror of the land-community to plain member and citizen of it. It implies respect for his fellow-members, and also respect for the community as such.
>
> In human history, we have learned (I hope) that the conqueror role is eventually self-defeating. Why? Because it is implicit in such a role that the conqueror knows, ex cathedra, just what makes the community clock tick, and just what and who is valuable, and what and who is worthless, in community life. It always turns out that he knows neither, and this is why his conquests eventually defeat themselves.
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> Aldo Leopold, A SAND COUNTY ALMANAC 204 (Oxford U. Press, 1968).

All members of the land community are therefore valuable both because of the roles they play but also simply because they exist. As humans identify and try to value ecosystem services they run at least two risks. First, species that do not appear to play functional roles that benefit humans may not be valued and therefore may not be protected.

> One basic weakness in a conservation system based wholly on economic motives is that most members of the land community have no economic value. Of the 22,000 higher plants and animals native to Wisconsin, it is doubtful whether more than 5 per cent can be sold, fed, eaten, or otherwise put to economic use. Id, at 210.

Another risk is that we are more ignorant than we are informed about ecosystem processes, thus there is a good chance we fail to identify, and therefore fail to value and protect critical parts of the whole. That said, the emergence of the ecosystem service concept has helped the public comprehend the critically important life-supporting processes performed by the ecosphere. That nutrients are recycled, water is cleaned and many other essential ecosystem activities occur at no expense to human society has led to them being taken for granted. There may be no expense when ecosystems are functioning, but when they are damaged or destroyed, the techno-industrial replacements, if they exist, can be extremely costly. But many ecosystem services have no suitable replacement.

II. GRASSLAND SOILS EXPLOITED FOR AGRICULTURE

Agriculture is thought to have first originated in areas with floodplains and forests; floodplains because they had little vegetation that needed clearing and forests because clearing patches of the landscape with slash and burn was also energetically feasible using stone tools.[8] Grasslands were more difficult to clear with stone tools and were not as easily subdued by Neolithic farmers.[9] Eventually farmers did manage to convert the perennial grass and forb vegetation of grasslands to agriculture and were rewarded with access to new soil types, among them the highly fertile Mollisols.[10]

What began as local patchwork exploitation of grassland soils for annual grain agriculture was gradually scaled up across entire landscapes. Today, less than 10% of North America's Great Plains prairies that existed before the arrival of Europeans remain today.[11] The disappearance of grasslands is not limited to temperate regions either. Fifty percent of Brazil's Cerrado grassland biome has been converted to agriculture.[12] As permanent perennial vegetation was replaced with annual crops that leave bare soil exposed for months of every year, the ecosystem services that characterized the intact grassland ecosystem gave way to ecosystem disservices. Of course, there was one key ecosystem service that was greatly improved with grain agriculture, and that was the provisioning service of food production. It seems obvious, but is important to point out that it *was* in fact food production, and not some consideration of sustainability or resilience that motivated this massive ecosystem conversion to croplands. Thus as humans we find ourselves with an unprecedented population profoundly dependent on a food- producing ecosystem of our design that is highly productive, but ultimately unsustainable.[13]

8. MARCEL MAZOYER & LAURENCE ROUDART, A HISTORY OF WORLD AGRICULTURE: FROM THE NEOLITHIC AGE TO THE CURRENT CRISIS 87, 260 (2006).

9. *Id.*

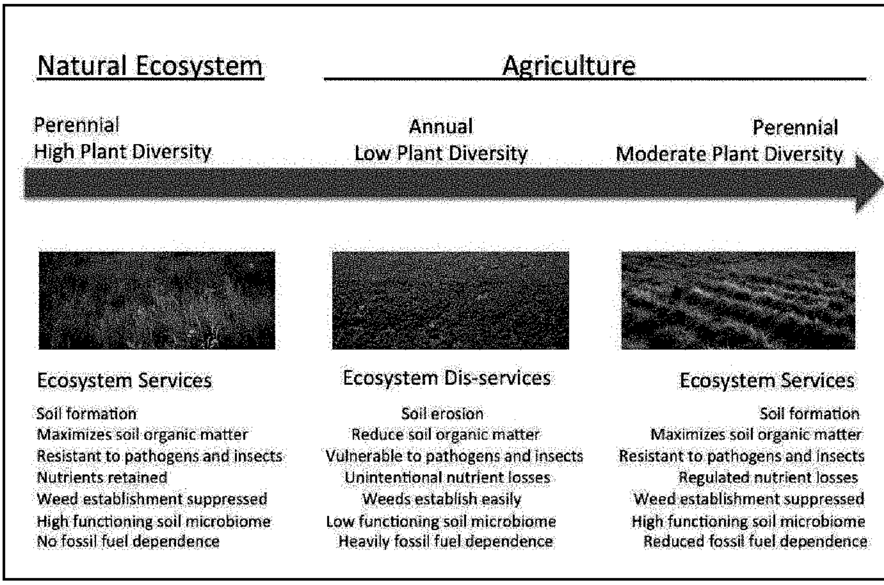
10. Mollisol is the soil type (or "order") as designated by the USDA classification system that forms under grasslands. *See* NYLE C. BRADY & RAY R. WEIL, ELEMENTS OF THE NATURE AND PROPERTIES OF SOILS 78 (3d ed. 2010).

11. Thomas H. De Luca & Catherine A. Zabinski, *Prairie Ecosystems and the Carbon Problem*, 9 FRONTIERS ECOLOGY & ENV'T 407, 407 (2011).

12. David M. Lapola, et al., *Pervasive Transition of the Brazilian Land-use System*. 4 NATURE CLIMATE CHANGE 27, 29 (2014).

13 WES JACKSON, CONSULTING THE GENIUS OF THE PLACE 100–30 (2010).

Figure 1. The evolution of ecosystem services and disservices in agriculture



A. Soil formation and erosion

The degradation of the soil resource that has resulted from the conversion of natural ecosystems to annual crop agriculture is arguably the greatest ecosystem disservice that will be addressed in this article. Most people have a general sense of what is meant by "soil", but to fully appreciate the impact of human activities on this resource it helps to have a finer understanding of what it is and how it is formed. Soil, the thin membrane-like coating that forms over much of the Earth's continents, is in many respects formed by the growth and decomposition of plants and also is required for most plants to grow[14]. Other organisms such as microbes contribute to soil formation as well, but plants are unique in that through photosynthesis, they provide the organic matter on which all other organisms depend.[15] Many people think of soils as being comprised primarily of minerals, but they are actually only about half mineral, about 1-10% organic matter (of which ~58% is carbon), and the rest is pore space that is either occupied by water or air.[16]

14. BRADY & WEIL, *supra* note 10, at 2, 44–45.

15. F. STUART CHAPIN, III ET AL., PRINCIPLES OF TERRESTRIAL ECOSYSTEM ECOLOGY 68 (2011).

16. BRADY & WEIL, *supra* note 10, at 15.

Soils develop when new "parent material" is deposited or exposed on land.[17] Mineral parent material is either sediment, recently deposited lava or ash from a volcano, or newly exposed rock that formed under the Earth's surface.[18] Often times the first things to colonize new parent materials are primitive communities of plant-like organisms that include lichens, bryophytes, algae, bacteria and fungi.[19] Organic acids produced by these communities, coupled with the oxidizing effects of air and moisture begin to break down rock crystals and add small amounts of organic matter.[20] Plants eventually take root and accelerate soil development through the physical activities of roots and the chemical reactions and conditioning of organic matter.[21]

Some plants that colonize newly developing soils might initially be annuals, that is, plants that germinate from a seed, grow to maturity, set seed and die in one growing season. Annuals, however, quickly lose out in competition with perennial plants, which live for many years. Almost all terrestrial or land-based ecosystems become dominated by perennial plants because once perennials are able to establish as seedlings, they have an inherent advantage over annual plants at the beginning of a growing season.[22] Since annual plants have to re-start their growth cycle from a relatively small seed every year, they are vulnerable to being out-competed for sunlight or soil resources such as water by already established perennial plants which that can emerge quickly from dormancy at the end of winter, or a dry season.[23] Annuals only persist as the dominant vegetation type past a few years in ecosystems that experience frequent, extreme disturbance, such as annual flooding along large rivers, or landslides. There are a few exceptions such as the California grasslands in parts of the Sierra foothills that were converted from perennial to annual vegetation through livestock grazing and fire (such ecosystems still feature

17. CHAPIN, *supra* note 15, at 64–65.

18. BRADY & WEIL, *supra* note 10, at 33–35.

19. Timothy E. Crews et al., *Organic Matter and Nitrogen Accumulation and Nitrogen Fixation during Early Ecosystem Development in Hawaii*, 52 BIOGEOCHEMISTRY 259, 265 (2001).

20. CHAPIN, *supra* note 15, at 74.

21. *Id.*

22. It is useful to point out that the practices of tillage or herbicide use are carried out specifically to control vegetation that could compete with the crop. This includes eliminating the native vegetation that exists when agriculture is first established in a location, but most of the time, it involves eliminating or suppressing the vegetation that invades land that is already farmed; this vegetation is commonly known as weeds. Ecologically speaking, weeds establish in a place where one or more resources such as water, nutrients or sunlight are not fully appropriated by existing vegetation. As described above, during the process of succession, perennial vegetation outcompetes annual plants because it can more fully utilize available resources. This makes it more difficult for weeds to invade and establish in fully developed perennial ecosystems. In contrast, a freshly plowed field is the ideal habitat for weeds to invade and establish.

23. DAVID TILLMAN, RESOURCE COMPETITION AND COMMUNITY STRUCTURE 127–28 (1982).

woody perennial species[24]). These annual grasslands appear to have been losing organic matter steadily since conversion, representing a backwards trajectory in soil development.[25]

There are good reasons to hypothesize that soils cannot form under annual plant communities. However, since almost no natural terrestrial ecosystems are dominated by annual plant species it is not practical to test this hypothesis. David Montgomery has calculated that globally, the net median rate of soil formation (formation–erosion) is approximately 0.004 mm per year.[26] He further calculates that the median net rate of soil loss in tilled agriculture is 1.52 mm per year, and 0.065mm per year in no-till agriculture.[27] These rates of soil loss are 360 and 16 times the rate of soil formation, respectively. It is evident that annual crops exploit rather than build on the soil capital that developed under the perennial-dominated natural ecosystem that preceded agriculture.

Interestingly, perennials do not come to dominate ecosystems because they facilitate soil development—a process that happens over very long spans of time—but because they out-compete annuals.[28] And yet without perennials, it is arguable that soils would not develop in the first place, at least nothing close to the depth and organic enrichment of profiles that exist today.

Soil erosion can be viewed as an ecosystem disservice that replaced the ecosystem service of soil formation when croplands replaced grasslands and other natural ecosystems around the planet. When protective perennial vegetation is removed to make way for agriculture, the soil is exposed to wind, rain, and the effects of gravity for weeks and even months every year.[29] Soil is even vulnerable to erosion after a crop has been sowed until the young crop canopy closes which can also take many weeks.[30]

Not surprisingly the threat of soil erosion and other forms of degradation have been a problem of agriculture since it began. Indeed, the Fertile Crescent, where wheat was first domesticated in Mesopotamia, has been transformed in

24. California Central Valley grasslands, WORLD WILDLIFE FUND, https://www.worldwildlife.org/ecoregions/na0801 (last visited April 22, 2017).

25. Rebecca Ryals & Whendee L. Silver, *Effects of Organic Matter Amendments on Net Primary Productivity and Greenhouse Gas Emissions in Annual Grasslands*, 23 ECOLOGICAL APPLICATIONS 46, 46 (2013).

26. David R. Montgomery, *Soil Erosion and Agricultural Sustainability*, 104 PROC. NAT'L ACAD. SCI. 13268, 13270 (2007). Montgomery is a Professor of Earth and Space Sciences at the University of Washington and has published widely read scientific and lay texts describing the severe impacts that tillage has on soils and the sustainability of civilization.

27. *Id.*

28. TILLMAN, *supra* note 23, at 127–28.

29. DANIEL HILLEL, OUT OF THE EARTH: CIVILIZATION AND THE LIFE OF THE SOIL 38 (1992).

30. Karine Vezina et al., *Agricultural Land-use Patterns and Soil Erosion Vulnerability of Watershed Units in Vietnam's Northern Highlands*, 21 LANDSCAPE ECOL.1311, 1322 (2006).

many parts by agriculture into a wasteland. Soil degradation contributed to civilization decline in the Indus Valley, Greece, Italy, China and parts of Mesoamerica.[31] And the problem continues today. According to one calculation, twenty-four billion tons of soil are lost annually around the world—several tons for each person on the planet.[32]

When the rate of soil loss via erosion exceeds the rate of soil formation, as happens across many agricultural landscapes, the ecosystem is simply unsustainable. In the words of David Montgomery, "if agricultural erosion rates remain far beyond rates of soil production, global society will eventually be compelled to either adopt agricultural methods that sustain the soil or face increasing competition over a shrinking agricultural land base."[33]

This problematic tradeoff between sustenance and sustainability is what led Wes Jackson to write the influential book *New Roots for Agriculture* in which he proposed the creation of a new agriculture that is modeled after the prairie. By breeding perennial grain crops, including cereals, pulses[34] and oilseed crops, and by planting them in complementary arrangements, Jackson proposed that agriculture could be transformed from a soil degrading to a soil building activity.[35] This work has been pursued by The Land Institute in Salina, Kansas since Jackson's book in 1980, and has now spread to dozens of universities and research institutions around the world.[36]

B. Soil organic matter loss from tillage

Soil erosion is the most destructive form of soil degradation that results from the conversion of grasslands to croplands[37], but even when soil particles are not physically removed by wind or water, soils can lose a key component of what makes them productive: organic matter. Soil organic matter (SOM) is an umbrella term for a wide range of substrates that form in the decomposition process of plants, animals and soil microbes.[38] SOM is not a static property of soil, but rather reflects a dynamic equilibrium between inputs of new organic compounds from plants, originating from photosynthesis, and losses of organic matter from soil microbes metabolizing organic matter and respiring CO_2 to the atmosphere.[39]

31. HILLEL, *supra* note 26, at 4, 5, 169; DAVID MONTGOMERY, DIRT: THE EROSION OF CIVILIZATION 40, 46, 77 (2007).

32. *Id.* at 74.

33. MONTGOMERY, *supra* note 24, at 13271.

34. Seed crops specifically from the legume or Fabaceae family such as beans and peas.

35. WES JACKSON, NEW ROOTS FOR AGRICULTURE 130 (1980).

36. See map of Land Institute Research Partners. *Research Partners,* THE LAND INST. https://landinstitute.org/about-us/research-partners/ (last visited March 21, 2017).

37. JACKSON, *supra* note 35, at 13–14.

38. Brady & Weil, *supra* note 10, at 372.

39. Crews et al., *supra* note 6, at 226–28.

When grasslands are converted to croplands, this dynamic equilibrium between organic matter inputs and loses is dramatically altered resulting in substantial declines in overall SOM stocks.[40] Soil scientists recognize that plant roots represent the most important avenue by which new organic matter enters a soil profile.[41] Senesced plant parts such as leaves and wood that accumulate on the soil surface contribute to SOM as well, but less of those materials persist by becoming incorporated into soil aggregates. Perennial grasses and forbs, such as those that make up native grasslands, allocate anywhere from 50-67% of fixed carbon in root or root-like tissues belowground.[42] It is this investment that gradually builds the deep dark surface or "A" horizon that characterizes Mollisols, or grassland soils (Figure 2).[43] In addition to roots, most plants host networks of mycorrhizal fungi that act in some ways as filamentous root extensions, helping plants to explore larger soil volumes to scavenge nutrients, among other functions.[44]

In contrast to perennial plant species, annual species, which includes crops like wheat, corn and sunflowers, allocate on the order of 15-30% of their productivity belowground.[45] The reduction in organic matter inputs that occurs when perennial vegetation is replaced with annual crops is one reason why SOM declines with agriculture.[46]

Outputs or losses of organic matter increase when grasslands are converted to annual croplands. In undisturbed soils, organic matter is stabilized inside naturally forming soil clods or aggregates.[47] Soil scientists believe that this stabilization occurs because microbes have a difficult time accessing SOM when it is bound between slightly charged clay particles in the middle of aggregates.[48] A glue-like protein called glomalin that is produced by mycorrhizal fungi is thought to play an important role in stabilizing soil

40. *See generally* Eric A. Davidson & Ilse L. Ackerman, *Changes in Soil Carbon Inventories Following Cultivation of Previously Untilled Soils*, 20 BIOGEOCHEMISTRY 161, 161–93 (1993).

41. *See generally* Michael W. I. Schmidt et al., *Persistence of soil organic matter as an ecosystem property*, 478 NATURE 49, 49–56 (2011).

42. Benard Saugier et al., *Estimations of Global Terrestrial Productivity : Converging Toward a Single Number?*, *in* TERRESTRIAL GLOBAL PRODUCTIVITY 545 (Jacques Roy et al. ed., 2001).

43. CHAPIN, *supra* note 15, at 81.

44. *See generally* David D. Douds Jr. & Rita Seidel, *The Contribution of Arbuscular Mycorrhizal Fungi to the Success or Failure of Agricultural Practices*, *in* MICROBIAL ECOLOGY IN SUSTAINABLE AGROECOSYSTEMS 133–52 (2012).

45. Jan Goudriaan et al., *Productivity of Agro-Ecosystems*, *in* TERRESTRIAL GLOBAL PRODUCTIVITY 305 (Jacques Roy et al. ed., 2001).

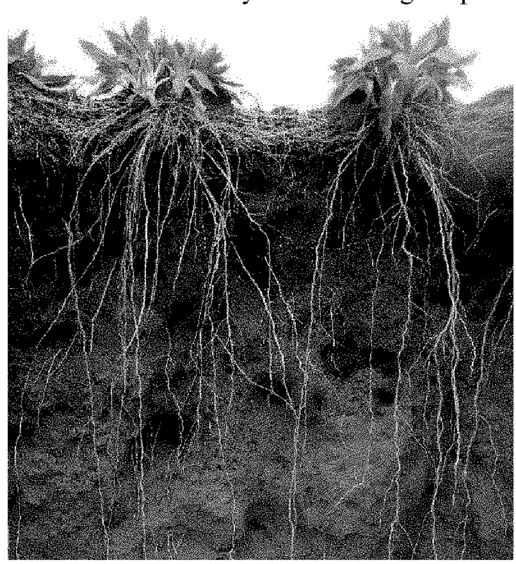
46. Timothy E. Crews & Brian E. Rumsey, *What Agriculture Can Learn from Natural Ecosystems in Building Soil Organic Matter*, 9 SUSTAINABILITY 578, 581-82 (2017).

47. A. Stuart Grandy & Jason C. Neff, *Molecular C Dynamics Downstream: The Biochemical Decomposition Sequence and its Impact on Soil Organic Matter Structure and Function*, 404 SCI. TOTAL ENV'T 297, 303 (2008).

48. *Id.*

aggregates.[49] When soils are plowed, mycorrhizal fungi are degraded, and the aggregates containing physically protected organic matter are broken open, exposing the SOM to microbial attack.[50] This enhancement of microbial activity happens every time a soil is tilled until 20-70% of the SOM accumulated under grassland vegetation has been lost at which time a new low SOM steady state takes place within about two decades.[51]

Figure 2 A 1.5 meter-deep soil profile planted to *Silphium integrifolium*, a perennial prairie species in the sunflower family. This species is being bred as an oilseed crop by researchers at The Land Institute. The soil is in the Mollisol order, and is characterized by a dark surface horizon called a mollic epipedon.[52] This dark horizon was formed by the inputs of organic matter from native prairie vegetation before the site was converted to agriculture. It is predicted that an agriculture consisting of perennial plants like *Silphium integrifolium* will begin to build soil organic matter in the same way as did the original prairie vegetation.[53]



The ecosystem disservice of SOM loss with conversion of grasslands to croplands is not only confined to soil degradation, but also impacts global

49. *See generally* Matthias C. Rillig, *Arbuscular Mycorrhizae, Glomalin, and Soil Aggregation*, 84 CAN. J. SOIL SCI. 355, 355–63 (2004).

50. Grandy, *supra* note 49.

51. Davidson & Ackerman, *supra* note 40, at 161–62; *see* R. Lal, *Sequestering Carbon in Soils of Agro-Ecosystems*, 36 FOOD POL'Y 533, 533 (2011) (explaining the range of how much soil matter is lost depends chiefly on soil texture, climate, crop choice, and management such as use of rotations or cover crops).

52. Brady & Weil, *supra* note 10, at 61.

53. Crews et al., *supra* note 6, at 226–28.

atmospheric CO_2 concentrations. DeLuca and Zabinski[61] estimate that the conversion of tall, medium and short grass prairies to croplands that took place across the Great Plains at the turn of the 20th century resulted in ~5 Pg of C emitted as CO_2 into the atmosphere. This release of carbon is of the same magnitude as that released from deforestation of the Brazilian Amazon rainforest.[62]

C. Implications of chemical weed control

In the last fifty years, agronomists have devised ways to substitute chemical control of weeds for the traditional mechanical controls of plowing and disking. "No-till" cropping involves carefully timed applications of herbicides to kill vegetation so that the soil remains intact with crop residues remaining on the surface.[63] In recent decades, the development and release of herbicide-tolerant crops has helped to increase adoption of no-till practices, especially in North and South America and, Australia.[64] By eliminating tillage, no-till farmers not only greatly reduce erosion, but they also address one of the two ways in which the ecosystem disservice of SOM decline occurs.[65] No-till does not enhance microbial consumption of SOM, and thus many have suggested that some fraction of the carbon that was lost following initial cultivation should be recaptured once no-till practices are adopted.[66] Interestingly, evidence for such re-accumulation of SOM under no-till is equivocal, leading to strong disagreements in the academic literature regarding the role of no-till in rebuilding SOM.[67]

No-till cropping systems, especially when expanded to include diverse cover crops between plantings of commercial crops, may be the most sustainable way of raising grains, with respect to soil health and protection. However, the method depends on applications of herbicides which carry a range of human health and ecosystem hazards. In 2014, the World Health Organization released a study suggesting that the most commonly used

61. DeLuca, *supra* note 11, at 410.

62. *Id.*

63. David R. Huggins & John P. Reganold, *No-Till: The Quiet Revolution*, 299 SCI. AM. 70, 73-74 (2008).

64. Rolf Derpsch et al., *Current Status of Adoption of No-Till Farming in the World and Some of its Main Benefits*, 3 INT'L J. AGRIC. & BIOLOGICAL ENG'G 1, 1, 5 (2010).

65. Crews & Rumsey, *supra* note 48, at 584.

66. Johan Six et al., *Soil Macroaggregate Turnover and Microaggregate Formation: A Mechanism for C Sequestration Under No-Tillage Agriculture*, 32 SOIL BIOLOGY & BIOCHEMISTRY 2099, 2099 (2000).

67. A.J. VandenBygaart, *The Myth That No-Till Can Mitigate Global Climate Change*, 216 AGRIC., ECOSYSTEMS & ENV'T 98, 98–99 (2016).

herbicide in the world—-glyphosate[68]—-is a potential carcinogen.[69] Where it is widely used, the efficacy of glyphosate has declined as resistance to the herbicide has developed in 23 weed species.[70] This has compelled the herbicide industry to develop crops that are tolerant of herbicide cocktails, which are expected to carry greater health risks than singular glyphosate applications.[71]

Aside from issues surrounding herbicide use, no-till approaches to weed control will not accumulate levels of soil organic matter attained by the natural ecosystems that preceded agriculture because annual crops do not allocate as much productivity to roots as perennial species.[72] There have not been any formal studies to date measuring the soil carbon accumulation under perennial grain proto-crops under development, however there exist numerous studies on lands that have been converted from annual cropping to perennial grasslands or perennial cellulosic biofuel crops that suggest accumulation rates of 0.33-1.88 t carbon ha^{-1} yr^{-1}.[73] These rates have been found to persist for one or two decades, and then gradually decline until no net carbon is sequestered after fifty years.[74] The wide range of soil carbon sequestration values reflects site-specific differences in soil texture, climate, vegetation composition, and degree of soil degradation experienced under agricultural management.[75]

D. Nutrient retention and loss

I have made the case thus far that natural perennial grasslands build soils, which includes SOM, whereas annual croplands commonly degrade or lose soils. More difficult to observe, but no less important is the well-developed capacity for grasslands to retain critical nutrients for plant growth, and the tendency for annual croplands to lose them. In 1975, ecologists Peter Vitousek and William Reiners published what is now a classic paper in ecology titled "Ecosystem succession and nutrient retention: a hypothesis".[76] In this paper the authors explain how highly disturbed ecosystems are predicted to leak

68. Produced commercially by Monsanto Corporation as Roundup™, *Glyphosate and Roundup Brand Herbicides*, MONSANTO, http://www.monsanto.com/glyphosate/pages/default.aspx (last visited March 21, 2017).

69. Daniel Cressey, *Widely Used Herbicide Linked to Cancer*, NATURE (March 24, 2015), http://www.nature.com/news/widely-used-herbicide-linked-to-cancer-1.17181.

70. Ian Heap, *Herbicide Resistant Weeds*, *in* INTEGRATED PEST MANAGEMENT 281–82 (D. Pimentel & R. Peshin, eds., 2014).

71. *Lawsuit Challenging EPA Approval of Harmful Herbicide Advances*, CTR. FOR FOOD SAFETY (Oct. 26, 2015), http://www.centerforfoodsafety.org/press-releases/4103/lawsuit-challenging-epa-approval-of-harmful-herbicide-advances#.

72. Saugier, *supra* note 42.

73. Crews & Rumsey, *supra* note 48, at 586.

74. *Id.*

75. Brady & Weil, *supra* note 10, at 383–85.

76. Peter M. Vitousek & William A. Reiners, *Ecosystem Succession and Nutrient Retention: A Hypothesis*, 25 BIOSCIENCE 376, 376 (1975).

prodigious quantities of nutrients, but when these same ecosystems are allowed to undergo ecosystem development over the course of succession[77], nutrients become much more highly regulated and tightly retained, resulting in very low leakage to adjacent landscapes, rivers or lakes.[78] While Vitousek and Reiners were describing the effects of extreme natural disturbances such as landslides or catastrophic fires or floods, their model describes precisely what happens to ecosystem nutrient retention in annual croplands that are disturbed by tillage. The main difference between natural ecosystems and agroecosystems, is the former experience extreme disturbances very infrequently, while the latter experience them every time the ground is plowed, disked or tilled. I have suggested, along with other researchers, that the annual grain crop ecosystem is likely the most disturbed ecosystem on the planet when areal extent, frequency and intensity of disturbance are considered together.[79]

As predicted by Vitousek and Reiner's model, intact perennial grasslands are extremely efficient at taking up nutrients such as nitrogen from both shallow and profound soil depths over a long growing season, which in temperate areas begins early in the spring and ends late in the fall.[80] Consistent with nutrient uptake patterns they also experience very low nutrient losses either via surface runoff or leaching through the soil profile.[81] This high degree of nutrient retention is one reason why grasslands can maintain high levels of productivity with very low nutrient inputs.[82] Even when grasslands experience the natural disturbances of fire or grazing, perennial plants re-grow with minimal disruption to nutrient uptake patterns.[83] Overall, water that leaves natural perennial grasslands is remarkably clean and free of nutrients.[84] When grasslands are converted to croplands, the ecosystem service of nutrient retention gives way to the ecosystem disservice of nutrient loss and related excessive freshwater or marine algae growth.[85] While many elements that make up soil can exit croplands at times of the year when crops are absent or undeveloped, the essential plant nutrients nitrogen (N) and phosphorus (P) are

77. Succession is an overarching term in ecology describing directional changes in the composition of biological communities and their ecosystem processes through time, *see* CHAPIN, *supra* note 15, at 348.

78. Vitousek & Reiners, *supra* note 69, at 378.

79. Crews et al., *supra* note 6, at 226.

80. Robert B. Woodmansee, *Additions and Losses of Nitrogen in Grassland Ecosystems*, 28 BIOSCIENCE 448, 448 (1978); Walter K. Dodds et al. *Nitrogen Transport from Tallgrass Prairie Watersheds*, 25 J. ENVIRON. QUAL. 973, 973-81 (1996); Kevin C. Masarik et al., *Long-Term Drainage and Nitrate Leaching below Well-Drained Continuous Corn Agroecosystems and a Prairie*, 5 J. ENVIRONMENTAL PROTECTION 240, 240 (2014).

81. Woodmansee, *Supra* note 73; Dodds et al., *Supra* note 73; Masarik et al., *Supra* note 73.

82. *See generally* John M. Blair et al., *Terrestrial Nutrient Cycling in Tallgrass Prairie*, *in* GRASSLAND DYNAMICS 222–36 (Alan K. Knapp et al. ed., 1998).

83. *Id.* at 239.

84. Woodmansee, *supra* note 73; Masarik, *supra* note 73.

85. Also referred to as eutrophication

particularly important. These two nutrients commonly interact to control how much algae grows in lakes and rivers.[86] Phosphorus does not leach very much although small amounts can be carried by water in different forms down through a soil profile into groundwater and eventually to rivers or lakes.[87] More commonly phosphorus is lost from landscapes via overland runoff[88]. Nitrogen on the other hand, is readily carried in the form of nitrate in water that leaches through soils ultimately flowing into rivers and lakes.[89] Freshwater eutrophication does happen naturally in certain situations, but it has become extremely common, even the norm, for lakes and rivers in heavily fertilized agricultural regions to become eutrophic for extended periods in most summers.[90]

Nitrogen, in the form of nitrate, not only plays a damaging role in stimulating algae growth in rivers and lakes, but also in coastal marine ecosystems. For example, in the Gulf of Mexico, a large dead zone forms every summer as a consequence of the Mississippi river delivering nitrate from upstream point and non-point sources.[91] It is clear that this nitrate loading increased substantially during the 20th century.[92] The most important of these sources is fertilized agricultural fields that cannot retain nitrate because soils are left with few or no active roots for a majority of every year.[93] Productivity of algae increases in response to the added nutrients and then decomposition of dead algae increases as well.[94] The organisms that decompose the algae draw down the oxygen concentrations in the water, which causes other oxygen-breathing organisms (like fish) to die.[95] There are more than 400 dead zones around the world with fertilizer loss being the most important driver.[96]

86. James J. Elser et al., *Global Analysis of Nitrogen and Phosphorus Limitation of Primary Producers in Freshwater, Marine and Terrestrial Ecosystems*, 10 ECOLOGY LETTERS 1135, 1135–36 (2007).

87. *See generally* Andrew N. Sharpley & Seppo Rekolainen, *Phosphorus in Agriculture and its Environmental Implications*, *in* PHOSPHORUS LOSS FROM SOIL TO WATER 1–53 (H. Tunney et al. ed., 1997).

88. *Id.*

89. CHAPIN, *supra* note 15, at 237.

90. UNITED NATIONS ENVIRONMENT PROGRAMME, *Why is Eutrophication Such a Serious Pollution Problem?*, http://www.unep.or.jp/ietc/publications/short_series/lakereservoirs-3/1.asp (last visited March 21, 2017).

91. *See generally* Whitney Brussard & R. Eugene Turner, *A Century of Changing Land-use and Water-quality Relationships in the Continental US*, 7 FRONTIERS IN ECOLOGY AND THE ENVIRONMENT 302, 302–07 (2009); *See also* Nancy N. Rabalais et al., *Dynamics and Distribution of Natural and Human-caused Coastal Hypoxia*, 7 BIOGEOSCIENCES DISCUSSIONS 585, 585–619 (2010).

92. Broussard & Turner, *supra* note 84; Rabalais et al., *supra* note 84.

93. R. Eugene Turner & Nancy N. Rabalais, *Linking Landscape and Water Quality in the Mississippi River Basin for 200 Years*, 53 BIOSCIENCE 563, 563–68 (2003).

94. Rabalais et al., *supra* note 84, at 585.

95. *Id.* at 587.

96. Robert J. Diaz & Rutger Rosenberg, *Spreading Dead Zones and Consequences for Marine Ecosystems*, 321 SCIENCE 926, 926 (2008).

Researchers who have documented the occurrence and underlying causes of the dead zone in the Gulf of Mexico have acknowledged the need for more functional, agricultural landscapes based on perennial crops:

> "...[W]ater quality may be rehabilitated if there are changes in land-use practices, such as reduction in cropland area dedicated to corn agriculture, increases in cropland diversity, or changes in intensive land management. Increasing the area of perennial crop systems could meet these objectives and could lead to major improvements in water quality, ecosystem services, and the production of the farming operation."[97]

Culman and colleagues at the University of Michigan compared the nitrogen retention between single species plantings of annual wheat and perennial wheatgrass or Kernza.[98] They found that once established, the perennial grain crop reduced total nitrate leaching by 86% compared to annual wheat. The different uptake efficiencies of perennial wheatgrass compared to wheat make sense when the rooting systems of these two species are compared, as in Figure 3.

Studies of nitrogen retention in diverse natural ecosystems have found that plant communities that include different and complementary functional groups[99], will take up different forms of nitrogen from the soil profile at different times of the growing season.[100] Niche complementarity for nitrogen coupled with the uptake efficiency of perennial roots helps explain the highly efficient nutrient retention demonstrated by natural grasslands. Studies such as these suggest that the integration of perenniality and multi-species complementarity into grain agriculture has the potential to correct the ecosystem disservice of nutrient leakage that is prevalent today in modern annual crop production.[101]

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97. Broussard & Turner, *supra* note 84, at 306.

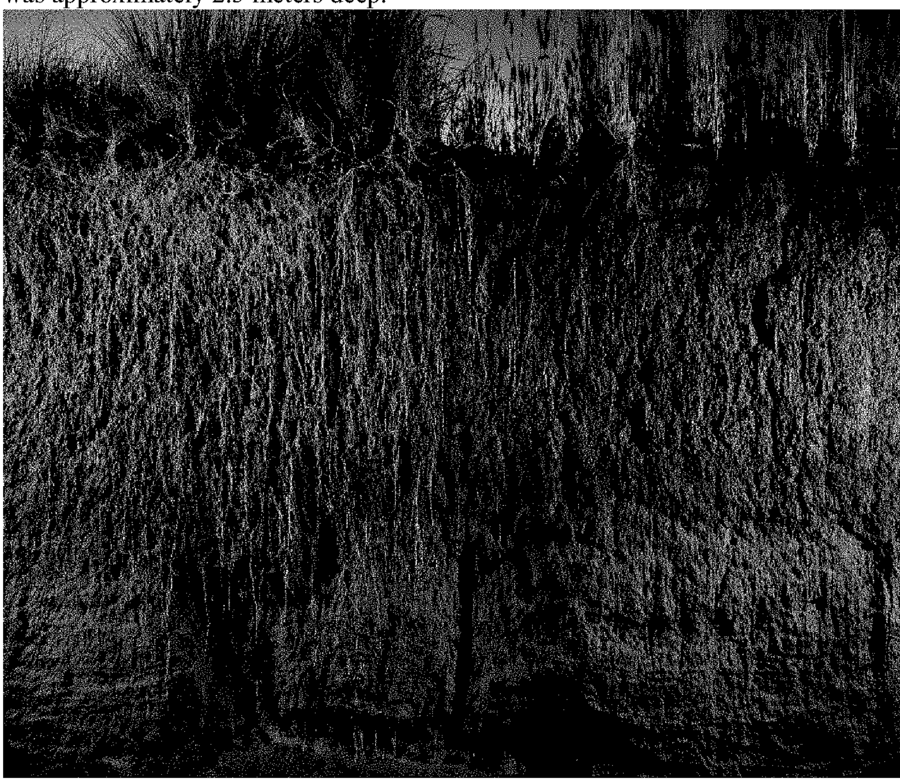
98. *See generally* Steve W. Culman et al., *Soil and Water Quality Rapidly Responds to the Perennial Grain Kernza Wheatgrass*, 105 AGRONOMY J. 735, 735–44 (2013).

99. Functional groups refer to categories of species that have similar functions in a plant community as opposed to a taxonomic group (genus, family, etc.). Typical functional groups in grasslands are warm or cool season grasses, forbs, and nitrogen fixers, early and late season producers.

100. *See generally* Ansgar Kahmen et al. *Niche Complementarity for Nitrogen: An Explanation for the Biodiversity and Ecosystem Functioning Relationship*, 87 ECOLOGY 1244, 1244–55 (2006).

101. Timothy E. Crews, *Perennial Crops and Endogenous Nutrient Supplies*, 20 RENEWABLE AGRIC. FOOD SYST. 25, 25–27 (2005).

Figure 3. Deep rooted intermediate wheatgrass (*Thinopyrum intermedium*) that produces the grain Kernza™ (left) and shallow rooted annual wheat (*Triticum aestivum*) on the right.[102] This soil profile that was excavated at The Land Institute was approximately 2.5 meters deep.



III. IMPORTANCE OF DIVERSITY

Up until this point in the article, I have described how soil "capital" accumulates under grasslands, and is depleted under annual grain crops. Now I will discuss the plant communities that characterize grasslands and croplands, and why plant communities matter in sustaining the productivity of natural and agricultural ecosystems. With few exceptions, naturally occurring plant communities are highly diverse and grasslands are no exception. When small areas of land are considered, grasslands host the greatest plant species richness of any ecosystem type. At scales of < 50 m^2, temperate grasslands have been found to include the greatest number of plant species, whereas at scales > 100 m^2, lowland tropical rainforests hold the record for diversity.[103] A mountain

102. The deep roots of the perennial grain crop Kernza™ are more efficient at taking up nutrients such as nitrogen deeper in the profile and for more months of the year compared to annual wheat. Photo by Jim Richardson and Jerry Glover.

103. J. Bastow Wilson et al. *Plant Species Richness: The World Records*, 23 J. OF VEGETATION SCIENCE 796, 796–802 (2012).

temperate grassland in Argentina was found to have 89 plant species in a 1 m^2. On a much larger scale, the 3500 ha. Konza Prairie Long Term Ecological Research Center in the Flint Hills of Kansas has a flora that includes 576 vascular plants.[104]

Diversity of plant species in ecosystems is thought to reflect historic pathogen pressures that resulted in one or a few dominant, productive species to lose competitive ability allowing for colonization of other species.[105] Once established, diverse plant communities can function to regulate and suppress widespread epidemics of pathogens.[106] The ecosystem service of plant diversity suppressing soil pathogens is illustrated in an experiment by Schnitzer and colleagues involving large pots filled with four soil treatments (direct from field, sterilized, sterilized + pathogens, and sterilized + beneficial fungi) and planted with one, five, ten or fifteen different plant species.[107] When grown as single species, plants in sterilized soils achieved significantly greater productivity than plants grown in field soils or sterilized soils with pathogens added. This suggests that under conditions of low plant diversity, pathogens can have a large negative impact on productivity. However, pathogen suppression of plant growth declined as species diversity increased to where at maximum diversity, there was no pathogen suppression evident.[108] This result suggests the possibility of reducing disease pressure on agricultural crops not through the application of toxic fungicides, but rather through the deployment of greater crop diversity.

104. Gene Towne, *Vascular Plants of Konza Prairie Biological Station: An Annotated Checklist of Species in Kansas Tallgrass Prairie*, KAN. STATE UNIV. (2002), http://www.konza.ksu.edu/data_catalog/flora_fauna/common%20names.txt.

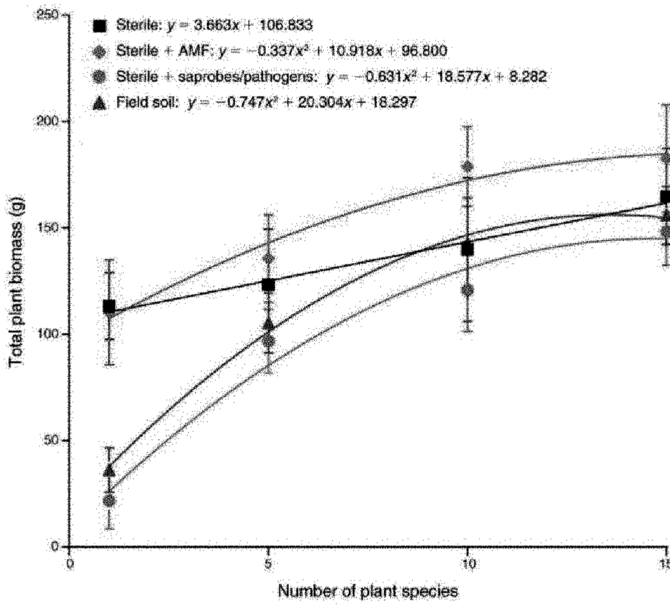
105. *See generally* James D. Bever et al., *Maintenance of Plant Species Diversity by Pathogens*. 46 ANNUAL REV. OF ECOLOGY AND SYSTEMATICS 305, 305–25 (2015).

106. *See generally* Val H. Smith et al., *Crop Diversification Can Contribute to Disease Risk Control in Sustainable Biofuels Production*, 13 FRONTIERS IN ECOLOGY AND THE ENVIRONMENT 561, 561–67 (2015).

107. *See generally* Stefan A. Schnitzer et al., *Soil Microbes Drive the Classic Plant Diversity-Productivity Pattern*. 92 ECOLOGY 296, 296–303 (2011).

108. *Id.*

Figure 4. Experimental results by Schnitzer and colleagues showing how plant community productivity increases with greater diversity through the suppression of soil pathogens. Design involved large pots filled with field or sterilized soils. The sterile soil treatments included no inoculums (black), mycorrhizal fungi inoculum (AMF) (red) or disease-containing inoculum (green).



Before the advent of industrialized agriculture, it was typical for farmers around the world to grow a high diversity of crop species often in polycultures.[109] The agricultural biodiversity they maintained was usually much lower than the species richness of the natural ecosystem agriculture replaced, but nevertheless polycultures and rotations were the norm.[110] Crop diversity often consisted of several primary crops (such as the classic Mesoamerican corn, bean, squash polyculture), along with a multitude of minor crops planted in break-rows or opportunistic gaps in fields.[111] Crop diversity was deployed in either time (rotations) or space (intercropping) and was maintained in part because of local demand for diverse foods that were only produced locally. Diversity was also maintained as a primary tool to control disease and insect pests, as there were few chemical or biological options for pre-industrial farmers[112]. There have been numerous hypotheses proposed to explain why diversity helps regulate the reproduction and spread

109. JOHN VANDERMEER, THE ECOLOGY OF AGROECOSYSTEMS 96 (2010).

110. MATT LIEBMAN, *in* AGROECOLOGY 205–18 (Miguel A. Altieri ed., 1995).

111. MIGUEL A. ALTIERI, AGROECOLOGY 126–43 (1995).

112. *See* Altieri, *supra* note 104; *See also* Stephen R. Gliessman, AGROECOLOGY: THE ECOLOGY OF SUSTAINABLE FOOD SYSTEMS 300–02 (2d ed. 2007).

of pest organisms in natural and agricultural ecosystems. Three of those classic hypotheses which are still widely considered today:

- Enemies hypothesis: vascular plant communities with higher diversity are more likely to provide continuous food and habitat resources that can sustain insect predator and parasitoid populations.[113]
- Diversity-Disease hypothesis: Transmission rates of diseases are proportional to the abundance of the host. If higher plant richness leads to lower abundances of most plant species, then disease severity would decrease accordingly.[114]
- Resource-concentration hypothesis: A disease or insect's success in establishing and spreading is proportionate to the patch size of the resource (e.g., crop plant) in time and space.[115]

As agriculture industrialized in the twentieth century, the diversity of crops grown decreased at the field, farm and regional scales.[116] Mechanization favored simple single-species cropping arrangements, and farmers shifted to relying on synthetic pesticides over diversity for crop protection.[117] Rotations with nitrogen fixing legume crops were replaced with continuous production of grains fertilized with nitrogen produced by the Haber-Bosch industrial synthesis of ammonia.[118] It is surprising to note that the increased use of pesticides since 1960 did *not* result in a corresponding decrease in crop losses to insect pests.[119] Indeed, Pimentel and colleagues reported that in spite of a 10-fold increase in insecticide use in the U.S. between 1945 and 1989, the share of crop yield in the U.S. lost to insects nearly doubled from 7% to 13%.[120]

The substitution of crop diversity by chemicals to suppress agricultural pests resulted in what may be the most publically acknowledged ecosystem disservice of industrial agriculture—pesticide poisonings. Most famously, Rachel Carson in her book *Silent Spring* chronicled how insecticides such as DDT could bioaccumulate through the food chain, resulting in health concerns

113. *See generally* David Pimentel, *Species Diversity and Insect Population Outbreaks*, 54 ANNALS OF THE ENTOMOLOGICAL SOCIETY OF AMERICA 76, 76–86 (1961).

114. *See generally* CHARLES ELTON, THE ECOLOGY OF INVASIONS BY PLANTS AND ANIMALS (1958).

115. *See generally* RICHARD B. ROOT, *Organization of a Plant-Arthropod Association in Simple and Diverse Habitats: The Fauna of Collards* (Brassica oleracea). 43 ECOLOGICAL MONOGRAPHS 95, 95–124 (1973).

116. Mazoyer & Roudart, *supra* note 7.

117. Power, *supra* note 5.

118. Timothy E. Crews & Mark B. Peoples, *Legume Versus Fertilizer Sources of Nitrogen: Ecological Tradeoffs and Human Needs*, 102 AGRIC. ECOSYST. ENVIRON. 279, 280 (2004).

119. *See generally* Erich-Christian Oerke, *Crop Losses to Pests*, 144 J. AGRIC. SCI. 31, 31–43 (2005).

120. DAVID PIMENTEL ET AL., *Assessment of Environmental and Economic Impacts of Pesticide Use*. THE PESTICIDE QUESTION 47 (1993).

and ecosystem impacts.[121] Many mark the birth of the environmental movement with the publication of Carson's book.[122]

Over the decades the agrochemical industry has responded to public concerns by developing toxins that better target the pest species and do not persist as long in the environment.[123] However, the recent controversy around neonicotinoid insecticides and their link to honey-bee colony collapse disorder demonstrate how even with careful testing, there can easily be unpredictable and unacceptable ecosystem impacts that result from widespread application of toxins.[124] Moreover, farmworkers and rural residents are frequently exposed to dangerous levels of pesticides[125]. Exposure can be especially problematic in less developed countries where warnings on imported pesticides may not be in the local language or regulations may not be enforced.[126]

It is clear that greater crop diversity—both in species and varieties—are necessary at field, farm, and regional scales to eliminate dependence on synthetic pesticides and the ecosystem disservices they deliver. But the question of how much diversity and of what type is salient in the design of a resilient natural systems agriculture. A significant difference between annual and perennial cropping systems is that disease and insect cycles can be disrupted in the former by deploying diversity through rotations. When a farmer replaces wheat with canola in a rotation, the populations of pest organisms that favor wheat are reduced.[127] Since it is not possible to disrupt a pest organism by removing its host in a perennial system, diversity needs to be deployed in some type of polyculture arrangement. For example varietal diversity can help maintain the efficacy of natural or introduced pest resistance genes. Zhu found in the Yunnan Province of China that when a susceptible rice strain was grown in diverse mixtures with more resistant varieties of the same species, the proportion of plants affected by the panicle blast fungus (*Magnaporthe grisea*) was reduced to 1.2% compared to 20% in monoculture.[128] The work of designing polycultures will never be complete as pest organisms are always evolving to overcome barriers that restrict their

121. RACHEL L. CARSON, SILENT SPRING (1962).

122. Eliza Griswold, *How 'Silent Spring' Ignited the Environmental Movement*, THE NEW YORK TIMES MAGAZINE (Sep. 21, 2012).

123. MONTAGUE YUDELMAN ET AL., PEST MANAGEMENT AND FOOD PRODUCTION: LOOKING TO THE FUTURE 20 (1998).

124. *See* Xerces Society for Invertebrate Conservation, *Neonicotinoids and Bees* (2016) http://www.xerces.org/neonicotinoids-and-bees/.

125. *See generally* Joan D. Flocks, *The Environmental and Social Injustice of Farmworker Pesticide Exposure*, 19 GEO. J. ON POVERTY L. & POL'Y 255, 255–82 (2012).

126. *See generally* Chandrasekharan N. Kesavachandran et al., *Adverse Health Effects of Pesticides in Agrarian Populations of Developing Countries,* 200 REV. ENVIRON. CONTAM. TOXICOL. 33, 33–52 (2009).

127. Barry M. Cunfer et al., *Effect of Crop Rotation on Take-all of Wheat in Double-Cropping Systems*, 90 PLANT DISEASE 1161, 1161–66 (2006).

128. Youyong Zhu et al. *Genetic Diversity and Disease Control in Rice*, 406 NATURE 718, 718–22 (2000).

reproductive success, but diversity can potentially slow down evolution to a manageable rate.

Figure 5. Polyculture of intermediate wheatgrass (*Thinopyrum intermedium*) and the perennial legume alfalfa (*Medicago sativa*) grown at The Land Institute.

IV. SOLAR VERSUS FOSSIL ENERGY

> In spite of many differences in agronomic practices and in cultivated crops, all traditional agricultures shared the same energetic foundations. They were powered by the photosynthetic conversion of solar radiation. Photosynthesis produced food for people, feed for animals, recycled wastes for the replenishment of soil fertility, and fuels for smelting the metals needed to make simple farm tools. Consequently, traditional farming was fully renewable.[129]

Agriculture is an energy-acquiring activity, and before the widespread adoption of fossil fuels, it was a thermodynamic necessity that more food

129. VACLAV SMIL, ENERGY IN WORLD HISTORY 28 (1994).

calories be produced by an agroecosystem than were used to grow the food.[130] While use of some fossil fuels such as coal had been underway for hundreds of years, the nineteenth century marked a transition from a solar to a fossil fuel economy in industrialized nations.[131] This transition deeply penetrated agriculture such that today, humans have figured out how to address virtually every ecological limiting factor to crop growth—nutrients, water, insect herbivory, weed competition, disease—with fossil fuels.[132] Indeed, of the energy required to "farm" a typical acre of corn in the U.S. today, 99.95% of the calories used originate from fossil fuels.[133] It is not uncommon today in industrialized cropping systems to expend four times the fossil fuel calories growing food such as tomatoes, than the food itself contains.[134]

Fossil fuels have not only been applied to ecological limiting factors in food production, but also social limiting factors such as labor.[135] David and Marcia Pimentel of Cornell University have calculated that one gallon of gasoline can deliver the "work" energy equivalent of 100 hours of human labor, or ~2.5 weeks of work at eight hours per day.[136] The cost of a gallon of gasoline compared to 100 hours of human labor, helps explain the extent to which fossil fuels have been substituted extensively for human and animal labor in industrial agricultural systems.

The U.S. food system as a whole, which includes food production, transportation and preparation, was estimated to use 15.7 percent of the national energy budget in 2007.[137] This represented an increase from 12.2 percent in 1997. The 2007 value is similar to estimates other developed countries as a whole where about 15 percent of all commercial energy is expended in the food system with about 6 percent used on-farm.[138]

As in other parts of the economy, profound dependence on fossil fuels in agriculture is connected to a wide range of ecosystem disservices associated with climate change.[139] Impacts associated with climate change include rising sea level, declines in native species, increases in introduced species, extreme

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130. Gliessman, *supra* note 105, at 655–61.

131. Smil, *supra* note 122, at 157.

132. DAVID PIMENTEL & MARCIA H. PIMENTEL, FOOD, ENERGY, AND SOCIETY 105 (3d ed. 2008).

133. *Id.* Calculation based on the proportion of kilocalories expended in labor as a fraction of the total kilocalorie expenditure per area of land.

134. *Id.* at 126.

135. *Id.* at 12.

136. *Id.*

137. Patrick Canning et al., *Energy in the U.S. Food System*, USDA ECONOMIC RESEARCH REPORT NUMBER 94 iv (2010).

138. PIMENTEL & PIMENTEL, *supra* note 125, at 154.

139. Environmental Protection Agency, *Climate Change Impacts*, https://www.epa.gov/climate-impacts (last viewed on March 22, 2017).

weather events, expanded ranges of diseases and disease vectors.[140] To the extent that all branches of industrial economies will need to drastically decrease fossil fuel dependence over the next decades in the face of climate change, making agriculture a solar, renewable enterprise will likely be a priority. However, the idea of replacing gasoline, diesel and other fossil fuel-derived inputs into agriculture with human or animal labor could prove challenging on many fronts. In this context, the development of agricultural systems that require less energy to maintain would have significant advantages. Modelling agriculture after perennial grasslands could reduce the energy inputs required by modern annual systems. As Pimentel and Pimentel point out, "[i]f the agricultural production system could be designed to more closely resemble natural ecological systems, it would require fewer energy inputs and be more productive and sustainable. [141]"

This is expected to be true because ecological processes such as biological nitrogen fixation take the place of energy-expensive inputs such as synthetic nitrogen fertilizers.[142]

V. CONCLUDING REMARKS

Humans have become reliant on a food-producing ecosystem that is not sustainable. It is not sustainable because it commonly loses soil faster than soil is formed, it loses soil organic matter, it leaks nutrients and other chemicals which pollute water bodies, it invites weeds, pest insects and diseases, it threatens pollinators, and it now relies on vast expenditures of fossil fuels to maintain production. In general, native ecosystems do not have or cause these problems. As Pimentel and Pimentel suggest above, if our agriculture could be designed to function more like natural ecosystems, then it would be easier to maintain, more ecologically sound and sustainable. These ideas have been voiced by Wes Jackson, the co-founder of The Land Institute, since 1980 when he wrote *New Roots for Agriculture*.[143] I have argued here that the two greatest obstacles standing in the way of a more natural systems-inspired agriculture, is the existence of perennial crops, and knowledge on how to assemble and maintain a wide diversity of perennial crops on the landscape. Work on developing perennial grain crops is receiving considerable attention[144] but projects take decades to bring to fruition, and more participants are needed to develop perennial crops suitable for the many cultures and geographic settings around the world. Humans now have the necessity and the capacity to capture

140. *Id.*

141. PIMENTEL & PIMENTEL, *supra* note 125, at 32.

142. *See generally* Erik Steen Jensen et al., *Legumes for Mitigation of Climate Change and the Provision of Feedstock for Biofuels and Biorefineries. A review*, 32 AGRON. SUSTAIN. DEV. 329, 329–64 (2012).

143. JACKSON, *supra* note 35.

144. *See generally, e.g.*, CATERINA BATELLO ET AL. PERENNIAL CROPS FOR FOOD SECURITY (2014); BETH BAKER, 67 BIOSCIENCE 325, 325–31 (2017).

the ecosystem services of the prairie by making agriculture resemble the prairie.